EXPRESS MAIL LABEL NO. EV442105515US

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United States Patent Application

for

THERMOACOUSTIC COOLING DEVICE

TO THE COMMISSIONER FOR PATENTS:

Your petitioner, BARTON L. SMITH, a citizen of the United States, whose post office address is 1252 Cedar Heights, Logan, Utah 84341, prays that letters patent may be granted to him as the inventor of a THERMOACOUSTIC COOLING DEVICE as set forth in the following specification.

THERMOACOUSTIC COOLING DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/457,619, filed March 25, 2003, which is hereby incorporated by reference herein in its entirety, including but not limited to those portions that specifically appear hereinafter, the incorporation by reference being made with the following exception: In the event that any portion of the above-referenced provisional application is inconsistent with this application, this application supercedes said above-referenced provisional application.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable.

BACKGROUND

1. <u>The Field of the Invention.</u>

The present disclosure relates generally to cooling devices, and more particularly, but not necessarily entirely, to cooling devices having thermoacoustic engines for producing synthetic jets.

2. <u>Description of Related Art.</u>

It is beneficial to remove heat from certain objects or areas in a variety of products and applications. For example,

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electronic devices, such as personal computers, servers, cameras, electrical appliances, etc., often have components, such as processors, microchips, or integrated circuits that generate heat. If this heat is not continuously removed, the electronic device may overheat, resulting in damage to the device and/or a reduction in operating performance. In order to avoid such overheating, cooling devices are often used in conjunction with electronic devices. Other non-electrical devices such as mechanical devices, optical devices, etc., may likewise generate heat and benefit from being cooled.

One type of cooling device is a heat sink cooling device. In such a device, the heat sink is formed of a material, such as aluminum, which readily conducts heat. The heat sink is usually placed on top of and in contact with the electronic device. Due to this contact, heat generated by the electronic device is conducted into the heat sink and away from the electronic device.

The heat sink may include a plurality of cooling fins in order to increase the surface area of the heat sink and, thus, maximize the transfer of heat from the heat sink into the surrounding air. In this manner, the heat sink draws heat away from the electronic device and transfers the heat into the surrounding air.

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In order to enhance the cooling capacity of a heat sink device, a fan is often mounted within or adjacent to the heat sink. In operation, the fan causes air to move over and around the fins of the heat sink device, thus cooling the fins by enhancing the transfer of heat from the fins into the ambient air.

Over the years, the power of electronic devices has increased and the size of the electronic devices has been reduced. Thus, the power density of the electronic devices has increased as well as the amount of heat generated by these devices. In order to adequately cool these higher powered electronic devices, cooling devices with greater cooling capacities have been required and the reliability of the cooling devices has become increasingly important. Heat sinks alone are often not adequate to cool modern electronic devices so that other cooling mechanisms, such as electrically powered fans, water cooling systems, heat pipes, etc., are required. The cooling mechanisms, in addition to the heat sinks, have become critical components to the reliability of various electronic devices. Fans in particular are subject to failure since they have mechanical and electrical components that can fail. Also, fans require external electrical power which can

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fail, or which can be depleted when drawn from limited power sources like batteries.

While much work has been done to produce highly reliable, cost competitive fans specifically for the microelectronics industry, many cases exist where the overall system reliability, or system availability, is paramount. In these cases, fans are often fitted with feedback mechanisms and are monitored by the operating system of the machine. The electrically powered fans consume additional electricity and have moving parts that are susceptible to wear and malfunction.

Another problem with fan assisted heat sink cooling devices is the noise generated by the fans, particularly in situations where larger and/or multiple fans are used to achieve increased cooling capacity. This is particularly a problem in desktop computers where users are commonly situated in close proximity to the machine. The problem is further aggravated in situations where multiple electronic devices and multiple cooling devices are mounted in the same computer case, as occurs in many high power computers.

The prior art is thus characterized by several disadvantages that are addressed by the present disclosure. The present disclosure minimizes, and in some aspects

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eliminates, the above-mentioned failures, and other problems, by utilizing the methods and structural features described herein.

The features and advantages of the disclosure will be set forth in the description which follows, and in part will be apparent from the description, or may be learned by the practice of the disclosure without undue experimentation. The features and advantages of the disclosure may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the disclosure will become apparent from a consideration of the subsequent detailed description presented in connection with the accompanying drawings in which:

FIG. 1 is a schematic cross-sectional perspective view of a thermoacoustic cooling system;

FIG. 1a is an exemplary graphical representation of the temperature at different points along the thermoacoustic cooling system;

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FIG. 1b is a schematic cross-sectional perspective view of an alternative thermoacoustic cooling system with a resonator having closed ends;

FIG. 2 is a schematic view of a thermoacoustic standing wave engine;

FIG. 3 is an enlarged breakaway schematic view of an orifice in a thermoacoustic engine;

FIG. 3a is an enlarged breakaway schematic view of an orifice in an alternative embodiment thermoacoustic engine;

FIG. 4 is a schematic view of an alternative embodiment thermoacoustic engine;

FIG. 4a is a schematic view of the alternative embodiment thermoacoustic engine of FIG. 4 with the resonator having a closed end;

FIG. 5 is a schematic cross-sectional perspective view of an additional alternative embodiment thermoacoustic cooling system;

FIG. 5a is a schematic cross-sectional perspective view of the alternative embodiment thermoacoustic cooling system of FIG. 5 with a resonator having closed ends;

FIG. 6a is a schematic perspective view of a stack formed of substantially parallel plates;

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FIG. 6b is a schematic perspective view of a stack formed of a spiral plate;

FIG. 6c is a schematic perspective view of a stack formed of a plurality of rods;

FIG. 6d is a schematic perspective view of a stack formed of a plurality of tubes;

FIG. 6e is a schematic perspective view of a stack formed of a triangular grid;

FIG. 6f is a schematic perspective view of a stack formed of a square grid;

FIG. 6g is a schematic perspective view of a stack formed of a hexagonal grid;

FIG. 6h is a schematic perspective view of a tortuous path stack;

FIG. 7 is a schematic perspective view of thermoacoustic cooling system used with a fan in a computer housing;

FIG. 8a is a perspective view of one embodiment of a heat exchanger in accordance with the principles of the present disclosure;

FIG. 8b is a perspective view of an alternative embodiment of a heat exchanger;

FIG. 8c is a perspective view of an additional alternative embodiment of a heat exchanger; and

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FIG. 9 is a schematic perspective view of the stack of FIG. 6b as it is being formed with a sacrificial material.

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DETAILED DESCRIPTION

For the purposes of promoting an understanding of the principles in accordance with the disclosure, reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the disclosure is thereby intended. Any alterations and further modifications of the inventive features illustrated herein, and any additional applications of the principles of the disclosure as illustrated herein, which would normally occur to one skilled in the relevant art and having possession of this disclosure, are to be considered within the scope of the disclosure claimed.

The publications and other reference materials referred to herein to describe the background of the disclosure, and to provide additional detail regarding its practice, are hereby incorporated by reference herein in their entireties, with the following exception: In the event that any portion of said reference materials is inconsistent with this application, this application supercedes said reference materials. The reference materials discussed herein are provided solely for their disclosure prior to the filing date of the present application. Nothing herein is to be construed as a

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suggestion or admission that the inventors are not entitled to antedate such disclosure by virtue of prior disclosure, or to distinguish the present disclosure from the subject matter disclosed in the reference materials.

It must be noted that, as used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Moreover, as used herein, the terms "comprising," "including," "containing," "characterized by," and grammatical equivalents thereof are inclusive or open-ended terms that do not exclude additional, unrecited elements or method steps.

As used herein, the term "join" means to put or bring together so as to make continuous or form a unit, or to put or bring together into close association or relationship. Accordingly, for example, joining a thermoacoustic engine with an object to be cooled includes situations in which the thermoacoustic engine contacts the object to be cooled, and/or situations in which the thermoacoustic engine is brought into close relationship with an object to be cooled without contact between the thermoacoustic engine and the object to be cooled.

As used herein, the term "transverse" refers to a position of an item that is across or crosswise relative to

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another item, including any relative position that is non-parallel.

Referring now to FIG. 1, a schematic cross-sectional perspective view of a thermoacoustic cooling system is shown indicated generally at 10. The thermoacoustic cooling system 10 may include an object to be cooled such as a chip 12, that may provide a heat source. It will be appreciated that the thermoacoustic cooling system 10 may also be used to cool any of a variety of objects besides the chip 12, such that any of a variety of heat sources may be used within the scope of the present disclosure. The chip 12 may be defined as an electrical component for carrying out a function. The chip 12 may include electronic components such as microelectronics, integrated circuits, or processors, for example, which may generate heat while carrying out the functions. The chip 12 may be made of a semiconducting material, such as silicon, which may be processed to have specified electrical characteristics. The object to be cooled, such as chip 12, may be formed in various different sizes and configurations within the scope of the present disclosure.

The thermoacoustic cooling system 10 may also include a thermoacoustic engine or device, indicated generally at 14, joined with the object to be cooled, such as the chip 12. The

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thermoacoustic engine 14, as referred to herein, may be defined as an energy conversion device in which heat flow from a high-temperature source to a low-temperature sink generates acoustic power. Operation of the thermoacoustic engine 14 is described more fully below, and is understood by those having ordinary skill in the relevant art.

The thermoacoustic engine 14 may include a resonator 16. The resonator 16 may have a first end 22 and a second end 24. Also, the resonator may include a wall 18 defining a chamber 20. The chamber 20 may contain a working fluid, such as air. However, it will be appreciated that other fluids may be used with the thermoacoustic engine 14 within the scope of the present disclosure. The wall 18 of the resonator 16 may form any cross-sectional shape and may have a length L that is longer than a width W of the resonator 16, as depicted in FIG. 2. The length L may be any length and may be a sub-multiple of a wavelength. For example, if both ends of the resonator 16 are open or if both ends of the resonator 16 are closed, the length L may be a multiple of a half of a wavelength, i.e. .5, 1, 1.5, etc. If only one end of the resonator 16 is closed and one end of the resonator 16 is open, the length L may be a multiple of a quarter of a wavelength, i.e. .25, .5, .75, etc. It will be understood that the width W may be

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smaller than the length L, such as a tenth of a wavelength for example. This allows the waves to form in a single direction along the length L of the resonator 16 rather than forming along both the length L and the width W as may occur if the length L and the width W are approximately equal. Accordingly, it will be understood that any of various ratios of length L to width W greater than 1:1 may be used within the scope of the present disclosure.

It will be understood that the resonator 16 may be formed such that one end of the resonator 16 may be open and one end may be enclosed by the wall 18, as shown in FIGS. 1, 4a, and 5a. Alternatively, the resonator 16 may be formed such that both the first end 22 and the second end 24 are enclosed by the wall 18, as shown in FIG. 1b. Also, embodiments of the resonator 16 may configured such that the wall 18 defines an opening at both ends as disclosed in FIGS. 4 and 5. It will also be understood that one or both the ends of the resonator 16 may be enclosed by structure other than the wall 18, such as the object to be cooled or chip 12.

It will be appreciated that the wall 18 of the resonator 16 may be formed of various different materials within the scope of the present disclosure. For example, any suitable rigid material that is capable of withstanding the

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temperatures generated by the object to be cooled may be used. One embodiment of the wall 18 may be formed of a stainless steel material, for example. Alternatively, the wall 18 may be formed of any other suitable metal, or any suitable non-metal material.

The thermoacoustic engine 14 may also include a stack 28 positioned inside the resonator 16. The stack 28 may have various different configurations within the scope of the present disclosure, such as stacks 28a-28h, as shown in FIGS. 6a-6h, respectively. For example, as best shown in FIG. 6a, the stack 28a may be configured as a series of thin, well spaced plates aligned substantially parallel to a longitudinal axis 26 of the chamber 20 and resonator 16. The stack 28a may also be formed from a bank of etched plates. For example, the stack 28a may be formed of "micro-machined" channels in silicon, as known to those having ordinary skill in the relevant art.

Alternatively, as shown in FIG. 6b, the stack 28b may be configured in the form of a spiral member. As shown in FIG. 9, the spiral member may be formed by sizing a suitable stack material 80, such as stainless steel, and placing a layer of sacrificial material 82, such as lead, on the stack material 80 such that no space resides between the stack material 80

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and the sacrificial material 82. The stack material 80 and sacrificial material 82 may be rolled together and heated such that the sacrificial material 82 melts and runs out leaving the spiral member of the stack material 80. It will be understood that the roll of stack material 80 may be placed in a sleeve or wrapper 88, as shown in phantom line in FIG. 9, in lieu of or in addition to a brace 86, to maintain the spiral shape, or the roll of stack material 80 may be tacked together, by one or more welds 84 for example, prior to removal of the sacrificial material 82. One method of holding the roll of stack material 80 together may involve forming the brace 86, by placing a powdered metal material on the stack 28b and welding or sintering the powdered metal with a laser, for example, such that the welded metal holds the stack material 80 in position. A cut may be placed in the stack material 80 such that the powdered metal may be placed in the cut to provide contact with three surfaces within the cut such that a stronger connection may be formed between the welded metal and the stack material 80.

Another method of holding the stack material 80 in place may involve forming the brace 86 of a plurality of crossing arms, and placing the brace 86 on an end of the stack material 80. The brace 86 may be formed of metal which may be brazed

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to the stack material 80 on an end of the spiral member to hold the stack material 80 in place. It will be understood that the above mentioned methods of holding the stack material 80 may be used alone or in combination. For example, the brace 86 may be used in combination with the one or more welds 84, or the brace 86 may be used without the one or more welds 84, or the one or more welds 84 may be used without the brace 86, for the purpose of holding the stack material 80 in place. It will be understood that various other methods of forming the stack 28b and holding the stack 28b together may be used within the scope of the present disclosure. It will also be understood that other sacrificial materials besides lead may be used, such as copper or plastics. Moreover, other methods of removing the sacrificial material may be used. For example, the sacrificial materials may be etched away, or lasers or chemical washes may be used to remove the sacrificial material 82 from the stack material 80.

It will also be understood that a stack 28c may be formed as a plurality of rods as shown in FIG. 6c, or a stack 28d may be formed as a plurality of tubes as shown in FIG. 6d. Also, stacks may be formed in various other configurations such as polygonal grids, including a triangular grid stack 28e, a square grid stack 28f, or a hexagonal grid stack 28g, as shown

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in FIGS. 6e-6g, respectively. Additionally, a tortuous path stack 28h may be formed as shown in FIG. 6h, or any other configuration of stack known to those skilled in the art may be utilized within the scope of the present disclosure to provide a channel to allow fluid to flow from one end of the stack to another. It will be understood that as referred to herein, the reference numeral 28 refers to the stack in general without regard to a specific configuration, including any of the stacks 28a-28h. The stack 28 may be configured to withstand the largest temperature generated by the chip 12 with minimal heat conduction. It will be appreciated that the stack 28 may be formed of various materials known in the art suitable for forming the stack 28.

Heat from the object to be cooled, such as the chip 12, may be transferred to the stack 28 in any manner known in the art, or by using any suitable heat-transferring device whether now known or later discovered. For example, the stack 28 may be positioned directly on the chip 12 such that heat from the chip 12 may be transferred to the stack 28 due to the contact between the chip 12 and the stack 28. Alternatively, a first heat exchanger 30, may be positioned near the stack 28 on a hot end 45 of the stack 28, and a thermal conducting material 33, such as copper, may be placed on the object to be cooled,

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such as the chip 12. The first heat exchanger 30 may be placed in a position in the thermoacoustic engine 14 so as to allow the first heat exchanger 30 to heat the fluid in the chamber 20 at the hot end 45 of the stack 28, and to avoid blocking the flow of fluid into the stack 28. The first heat exchanger 30 may also be formed of a material to conduct heat, such as copper.

The first heat exchanger 30 may have holes 32 inside the engine 14 to allow air flow therethrough. Thus, the first heat exchanger 30 may be formed in various configurations such as a grate-like heat exchanger 30a, as best shown in FIG. 8a, having elongate holes 32a. Alternatively, a heat exchanger 30b may be formed having circular holes 32b, as best shown in FIG. 8b. Also, a heat exchanger 30c may be formed as a screen of interwoven wires, for example. The heat exchanger 30c may have square openings or holes 32c, as best shown in FIG. 8c. It will be understood that the first heat exchanger 30 may have various other shapes compatible with the stack 28, and that the holes 32 may be formed in various other configurations within the scope of the present disclosure.

The first heat exchanger 30 may serve to maintain a high temperature at the hot end 45 of the stack 28 by transferring heat from the object to be cooled, such as chip 12. It will

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be understood that an alternative embodiment of the present disclosure may include an external heating means for heating the hot end 45 of the stack 28, in which heat is supplied from a source other than an object 12 to be cooled. Such an alternative embodiment may be used for any desired purpose, including use of the thermoacoustic engine 14 as an actuator, in which a synthetic jet produced operates to actuate something. Accordingly, the thermoacoustic engine 14 may be utilized to fulfill other purposes in addition to cooling objects, such as creating a synthetic jet for various uses, including uses known to those skilled in the relevant art. It will be understood that any suitable external heating means known to those skilled in the art may be used in accordance with the principles of the present disclosure. The side of the stack 28 opposite the first heat exchanger 30 may be in contact with the working fluid in the chamber 20 to form a cold end 46 of the stack 28.

Heat may be transferred from an object such as the chip 12 through the first heat exchanger 30 into the stack 28 and the chamber 20. One or more orifices 34 or slits may be formed in the wall 18 for providing a passageway for the working fluid to pass from the chamber 20 to a position outside the resonator 16. It will be understood that the term

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"orifices" as used herein shall be interpreted broadly to include any variety of openings, slits, or passages, without limitation to size, shape or configuration. In one embodiment, the one or more orifices 34 may be positioned on the wall 18 near the stack 28. However, it will be appreciated by those having skill in the relevant art, that the one or more orifices 34 may be located on the wall 18 on the second end 24 of the resonator 16, or at other positions on the resonator 16 within the scope of the present disclosure.

As shown in FIG. 1a, which shows a graphical representation of the temperature T of the thermoacoustic cooling system 10, the ambient fluid may have a temperature T_0 and the chip 12 may have a temperature T_{chip}. As heat moves from the chip 12 into the first heat exchanger 30, acoustic power may be generated in the stack 28 and converted to mean motions by the one or more orifices 34 in the wall 18. This mean flow may bring ambient fluid at temperature T_0 into the thermoacoustic engine 14 to cool the stack 28. The rejected heat may be carried out of the thermoacoustic engine 14 by the same mean motion. Accordingly, the temperature of the thermoacoustic cooling system 10 at the second end 24 may approach the ambient fluid temperature T_0.

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One exemplary embodiment of the thermoacoustic engine 14 may include a type of standing wave engine. The thermoacoustic engine 14 may include a tube or resonator 16 that may be approximately one half a wavelength long, or any other multiple of one half, such as approximately 1.5, 2.5, etc. As shown most clearly in FIG. 2, which shows a schematic view of a thermoacoustic engine 14, the working fluid in the chamber 20 may have a velocity amplitude, as represented by the graphical representation at 25 with respect to the axis 26. Fluid at the first end 22 and the second end 24 of the resonator 16 may have velocity "nodes" 38, or points with virtually zero amplitude of velocity. Whereas the working fluid near a center 27 of the resonator 16 may have a velocity antinode 42, or a point of maximum amplitude between adjacent nodes.

The working fluid in the chamber 20 may have a pressure amplitude as represented graphically at 29. Pressure antinodes 44, or points of maximum amplitude, may be located at the first end 22 and second end 24 of the resonator 16 coinciding with the velocity nodes 38. A pressure node 40 may be located near the center 27 of the resonator 16 coinciding with the velocity antinode 42.

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A tube such as the resonator 16 will resonate in such a way that one half of a wavelength resides in the tube. The wavelength of an oscillation of a sound wave is a function of the speed of sound, approximately 300 meters per second for atmospheric air, and the frequency of operation. Specifically, the wavelength λ is equal to a/f where a is the speed of sound and f is the frequency. Therefore, the overall length of the engine, L, is equal to $300/2f$. Since the speed of sound is fixed for atmospheric air when the temperature is constant, and assuming that the air temperature variation inside the thermoacoustic engine 14 is too small to significantly alter the speed of sound, the length of the engine L is the only parameter that determines the operating frequency f.

The stack 28 may be positioned in the resonator 16 in a location with significant velocity, but much lower velocity than at the antinode 42. This position minimizes viscous losses through the stack 28 and heat exchangers.

Acoustic work (and per unit time, power) is generated when a parcel of the working fluid, such as air, inside the stack 28 expands while pressure is high or contracts when pressure is low. This occurs if the parcel of working fluid undergoes a density cycle and a pressure cycle that are ninety

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degrees out of phase. The density cycle is generated by varying the temperature in a cyclic fashion, which occurs due to the motion of the parcel of working fluid in the stack 28. The oscillating motion of the parcel of working fluid in the stack 28 is caused spontaneously when the temperature difference across the stack 28 becomes large enough. Everywhere in the resonator 16, pressure and velocity are approximately ninety degrees out of phase. This means that the pressure and the position of a given fluid parcel are in phase.

In order to cause the fluid to undergo a temperature cycle that lags position (and thus pressure) by ninety degrees, it is necessary that the thermal contact between the stack 28 and the air be rather poor. If this is the case, as the fluid parcel moves back and forth in the stack 28 (and the pressure varies at the same time and in phase with it) the fluid parcel's temperature (and thus density) vary somewhat behind its position.

A measure of thermal contact is the ratio of the stack pore size, r, to the thermal penetration depth, δ_k. The thermal penetration depth δ_k may be described as the average distance over which a sound field interacts thermally with a body. The thermal penetration depth δ_k is a function of

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frequency ω and the thermal diffusivity k of the fluid: δ_k equals the square root of $2k/\omega$. Generally, standing wave engines operate best when the pore size is a few thermal penetration depths, such as within a range of approximately one to four thermal penetration depths for example. Therefore, once the working fluid and the frequency (length) are chosen, the optimal pore spacing may be fixed.

One embodiment of the thermoacoustic engine 14 may also include a second heat exchanger 31, as shown in dashed lines in FIG. 2. While the first heat exchanger 30 may serve to maintain the hot end 45 of the stack 28 at a high temperature, the second heat exchanger 31 may serve to maintain the cold end 46 of the stack 28 at a lower temperature. The heat supplied to the first heat exchanger 30 may be converted to oscillating power including the pressure amplitude 29 that is ninety degrees out of phase with the flow rate or velocity 25, while heat may be rejected by the second heat exchanger 31. The first heat exchanger 30 and the second heat exchanger 31 may straddle the stack 28. However, as discussed above, the cold end 46 of the stack 28 may be maintained at a lower temperature by allowing ambient air into the resonator 16 through the one or more orifices 34 without the second heat exchanger 31. Since heat exchangers inherently create large

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amounts of entropy, eliminating the second heat exchanger 31 may result in a very significant increase in the efficiency of the thermoacoustic cooling system 10.

It will be understood that the thermoacoustic engine 14 may make an audible sound. It may therefore be desirable to configure the thermoacoustic engine 14 so as to operate beyond the range of human hearing, whether above or below the range of human hearing, or near a limit of the range of human hearing. For example, thermoacoustic engine 14 that is 0.9 centimeters long will operate at 17 Khz, which will be undetectable to most people. At this frequency, a pore spacing on the order of 0.1 millimeters or 0.004 inches would be required.

It will be understood that in one embodiment of the present disclosure, the thermoacoustic engine 14 may be configured to make a sound that is within the range of human hearing. This may allow the thermoacoustic engine 14 to operate as an alarm. As heat is generated by an object such as a chip 12, the thermoacoustic engine 14 may make a sound indicating to a user that the chip 12 is heated, that the thermoacoustic engine 14 is cooling the chip 12, or that the temperature of the chip 12 is within a particular range. For

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example, the thermoacoustic engine 14 may make a sound when the chip 12 is too hot, too cold, or at a desired temperature.

In one embodiment of the present disclosure as shown most clearly in FIG. 1, the one or more orifices 34 may include a plurality of small orifices formed in the resonator 16 to allow fluid inside the chamber 20 to be exchanged with ambient fluid outside the resonator 16. It will be understood by those having skill in the relevant art, that the location, configuration, quantity, and distribution of the one or more orifices 34 shown in FIG. 1 is schematic and for illustrative purposes only, and that various different locations, configurations, quantities, and distributions of the one or more orifices 34 may be utilized within the scope of the present disclosure. For example, it will be understood that the one or more orifices 34 may be located in various locations in the resonator 16 such as in the wall 18 near the stack 28 extending radially or transverse to the axis 26, or in the second end 24 of the resonator 16 extending substantially parallel to the axis 26, or in various other locations. Providing the one or more orifices 34 with a small size may prevent the one or more orifices 34 from becoming significant to the acoustics or frequency of the thermoacoustic engine 14. The distribution of the one or more

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orifices 34 may allow them to be oriented in such a way as to cancel sound generated by the one or more orifices 34 and to minimize vibrations.

The flow of the working fluid through the one or more orifices 34 may create a synthetic jet, as indicated by reference numeral 36 in FIG. 1. An exemplary flow path of the cold working fluid coming into the engine may be depicted as shown at 37. A synthetic jet as referred to herein may be described as a mean fluid motion generated by high-amplitude oscillatory flow through an orifice or nozzle. Synthetic jets have a zero-net-mass-flux nature, in which the fluid is circulated such that the flow of fluid out of an opening is equal to the flow of fluid into the opening. Accordingly, the one or more orifices 34 may be configured as known to those of ordinary skill in the relevant area of the art, and as discussed in the following publications which are hereby incorporated herein by reference in their entireties: Barton L. Smith, Mark A. Trautman, and Ari Glezer, *Controlled Interactions of Adjacent Synthetic Jets*, American Institute of Aeronautics and Astronautics, AIAA 99-0669; and Barton L. Smith and Gregory W. Swift, *Synthetic Jets at Large Reynolds Number and Comparison to Continuous Jets*, American Institute of Aeronautics and Astronautics, AIAA 2001-3030, such that the

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thermoacoustic engine 14 produces power to form a synthetic jet 36 at each of the one or more orifices 34 to move the heated air in the chamber 20 away from the thermoacoustic engine 14, and allow ambient air to be drawn into the chamber 20. As such, the one or more orifices 34 may constitute part of a means for forming a synthetic jet for transporting a flow of fluid out of the chamber 20 of the thermoacoustic engine 14. The second law of thermodynamics requires that any cyclic heat engine reject heat to a lower temperature. In the present disclosure, heat may be rejected to the ambient, and the transfer of heat may be aided by the flow generated by the synthetic jet 36.

As shown in FIG. 3, which shows an enlarged breakaway schematic view of an orifice 34a in a thermoacoustic engine 14. The orifice 34a may be axisymmetric having a diameter D. Also, a stroke length L_o may be defined as the length of a slug of fluid 48 pushed from the orifice 34a during a blowing stroke. The blowing stroke may be described as a portion of the oscillation of the fluid in the resonator 16 which forces fluid out the orifice 34a. The slug of fluid 48 and the stroke length L_o are understood by, and may be determined by, those having ordinary skill in the relevant area of the art and as discussed in the above cited publications by Barton L.

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Smith in the American Institute of Aeronautics and Astronautics publications. It will be understood that in one embodiment of the present disclosure, as illustrated in FIG. 3a, the orifice 34a may include a neck length L_n. The stroke length L_o and the neck length L_n may be configured such that a ratio of the stroke length L_o over the neck length L_n is greater than 1.

For an axisymmetric orifice of diameter D, a synthetic jet forms when L_o/D is greater than 1. Below this level, a slug of fluid 48, such as a vortex ring, may form, but it is ingested during a suction stroke, or portion of the oscillation which draws a fluid into the orifice 34a. A synthetic jet 36 may be formed when each slug of fluid 48 or vortex ring that is ejected during the blowing stroke propagates downstream with sufficient speed to be out of the influence of the sink-like flow 37 during the suction stroke. Accordingly, the orifice 34a may be configured such that L_o/D is greater than 1 such that a synthetic jet 36 may be formed.

Embodiments of the one or more orifices 34 that are not axisymmetric may have a cross stream orifice width *h* rather than a diameter D. However, it will be appreciated that the side schematic view depicted in FIG. 3 is applicable to embodiments of the one or more orifices 34 that are either

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axisymmetric or non-axisymmetric. Accordingly, both the diameter D and the width h are shown in FIG. 3. For embodiments of the one or more orifices 34 that are non-axisymmetric, a synthetic jet may form when a ratio of the stroke length L_o over the width h is greater than some threshold. It will be appreciated that the one or more orifices 34 may be configured in any manner such that the ratio L_o/h is greater than this threshold so that a synthetic jet may be formed. In one exemplary embodiment, the synthetic jet formation threshold may be nominally constant and in the neighborhood of $1< L_o/h <10$. More specifically, the synthetic jet formation threshold may be in the range of $3< L_o/h <8$, or $5.5 < L_o/h <6.0$. It will be understood that the synthetic jet 36 may be pulsatile at locations close to the one or more orifices 34, whereas the synthetic jet 36 may be indistinguishable from a steady flow jet at increasing distances from the one or more orifices 34.

Those skilled in the art will understand that the thermoacoustic cooling system 10 may include any number of thermoacoustic engines 14 joined with the object to be cooled. Accordingly, where increased cooling capacity is needed, additional thermoacoustic engines 14 may be joined with the object to be cooled.

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It will be understood that the thermoacoustic cooling system 10 may be configured, in one embodiment, to transfer heat from the first heat exchanger 30 to the fluid at the cold end 46 of the stack 28. Accordingly, the chip 12 may only be cooled to a temperature as low as the temperature at the cold end 46 of the stack 28, which may be ambient temperature. This feature may differ from prior art thermoacoustic cooling systems which require power to operate a refrigerator. Such systems may generate temperatures that may be lower than ambient temperatures. However, it will be understood that an alternative embodiment of the present disclosure may include a stack cooling means to cool the cold end 46 of the stack 28 to temperatures below ambient temperatures. The stack cooling means may be formed in any manner known in the art and may be represented schematically by the second heat exchanger 31.

The thermoacoustic cooling system 10, using the thermoacoustic engine 14 may be configured to move heat away from the object to be cooled via forced air convection. The air motion may be generated from the heat dissipated by the object to be cooled. Therefore, the thermoacoustic cooling system 10 may be configured to operate with no external power. In fact, if an increase in power dissipation is experienced by the object to be cooled, the output of the thermoacoustic

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engine 14 may also increase thereby making the system inherently stable.

The performance efficiency of one embodiment of the present disclosure may be explained by the following example. Due to constraints imposed by the second law of thermodynamics, all heat engines have a theoretical upper bound on thermal efficiency that is a function only of the temperatures of the heat source and sink. This limit, called the Carnot Efficiency η, may be described by the following equation:

$$\eta = W/Q_{in} = 1 - T_{out}/T_{in},$$

where W is the power generated, Q_{in} is the heat transfer into the machine, T_{out} is the temperature of the sink, such as ambient temperature, and T_{in} is the temperature of the source, such as chip 12, in Kelvin. Chips generally have a temperature limit near 80 degrees C, and the ambient is usually room temperature or 20 degrees C. Accordingly, the best one can hope for under these conditions is a 17% thermal efficiency (1-293/353=17%). Real devices do not generally approach this efficiency, which assumes no entropy generation. Standing wave engines have been constructed that have

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efficiencies as high as 23% of Carnot Efficiency, which in the present example would equal a thermal efficiency of 3.9% (23% of 17%). Although this may initially appear to be low, consider that common fans integrated into heat sinks consume power on the order of one Watt. Assuming a chip dissipates 100 Watts, and given the 3.9% thermal efficiency, 3.9 Watts would be available for the cooling flow. It will be appreciated that the chip 12 and ambient may have other temperatures, and that other efficiencies may result within the scope of the present disclosure.

It will be appreciated that the thermoacoustic engine 14 may have no moving parts. This feature may increase the reliability of the thermoacoustic cooling system 10 as compared to cooling systems having moving parts, since moving parts are commonly susceptible to wear and malfunction. Moreover, the reliability of the present disclosure may be further enhanced since no external power may be required other than the heat from the object to be cooled. External power sources are also susceptible to failure and depletion which may reduce the reliability of cooling systems that rely on the external power sources. It will be appreciated, however, that the thermoacoustic engine 14 may also be used in combination with other cooling mechanisms, such as fans, that

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have moving parts and/or require external power sources. In such instances, the reliability of the cooling system may be enhanced since fewer moving parts and less external power may be required.

An exemplary embodiment of the thermoacoustic cooling system 10 used in combination with a fan 60 is shown schematically in FIG. 7. The thermoacoustic cooling system 10 may be used to cool a chip 12 such as a central processing unit enclosed in a computer housing 62. The thermoacoustic engine 14 may be used to remove heat from the chip 12 as discussed above, and the fan 60 may be used to remove the heat from the housing 62. It will be understood that various different cooling means rather than the fan 60, or in addition to the fan 60, in various different configurations, may be used in combination with the thermoacoustic cooling system 10.

Reference will now to made to FIG. 4 to describe an alternative embodiment of the present disclosure. As previously discussed, the presently described embodiments of the disclosure illustrated herein are merely exemplary of the possible embodiments of the disclosure, including that illustrated in FIG. 4.

It will be appreciated that the alternative embodiment of the disclosure illustrated in FIG. 4 contains many of the same

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structures represented in FIGS. 1-3 and 6-9, and only the new or different structures will be explained to most succinctly explain the additional advantages which come with the embodiment of the disclosure illustrated in FIG. 4.

An alternative embodiment thermoacoustic cooling system, indicated generally at 10a, is shown schematically in FIG. 4. The alternative embodiment thermoacoustic cooling system 10a may include an alternate embodiment thermoacoustic engine 14a which may be made to vibrate like a Helmholtz resonator. Accordingly, the alternative embodiment thermoacoustic engine 14a may sometimes be referred to as a Helmholtz resonator. An example useful in describing a Helmholtz resonator is a container such as a bottle having an open neck. When air is blown over the open end of the bottle, a whistling sound is made. The air inside the bottle acts as a spring, and the air inside the neck of the bottle vibrates in and out against the spring. In contrast, the thermoacoustic engine 14 depicted in FIG. 1 may be configured such that the fluid in the chamber 20 near the first end 22 and the second end 24 acts as a spring as the fluid in the central portion of the chamber 20 oscillates back and forth.

In the alternative embodiment thermoacoustic engine 14a, the frequency of operation is a function of the container

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volume and the size (diameter and length) of the neck in the top. The shape of the container has no effect on the operation of the Helmholtz resonator, and therefore a single unit could be built to cover any area. Air may be exchanged with the environment through a single hole.

The alternative embodiment thermoacoustic engine 14a may include a neck 52 on the second end 24. The neck 52 may have various lengths within the scope of the present disclosure. One embodiment of the neck 52 may have a minimum length defined by a thickness of the wall 18. Other embodiments of the neck 52 may extend distances beyond the thickness of the wall 18. The neck 52 may include an orifice 54 providing a passage from the chamber 20 to the ambient. It will be understood that the configuration of the orifice 54 may have an impact on the frequency of operation of the alternative embodiment thermoacoustic engine 14a. Oscillating movement of the fluid across the stack 28 due to the differential temperature between the first heat exchanger 30 and the cool fluid in the chamber 20 may cause the fluid in the neck 52 to move in and out of the neck 52 as the fluid in the chamber 20 operates as a spring. Accordingly, a synthetic jet may be formed and heat may be transferred to the ambient outside the chamber 20.

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In both the alternative embodiment thermoacoustic engine 14a as well as the exemplary embodiment thermoacoustic engine 14, heat moves from the object to be cooled into the first heat exchanger 30, if present, and into the stack 28. A small portion of the heat, such as a few percent, may be converted to acoustic power. The remainder of the heat may arrive at the cold end 46 of the stack 28 to be carried away by the motion of the ambient fluid flowing through openings in the chamber 20, and driven by the generated acoustic power in the chamber 20. As with the integrated fan/heat sink, it may then be necessary to move the heated fluid away from the device so that cool fluid may be ingested into the resonator 16.

Reference will now to made to FIG. 5 to describe an additional embodiment of the present disclosure. As previously discussed, the presently described embodiments of the disclosure illustrated herein are merely exemplary of the possible embodiments of the disclosure, including that illustrated in FIG. 5.

It will be appreciated that the additional embodiment of the disclosure illustrated in FIG. 5 contains many of the same structures represented in FIGS. 1-4 and 6-9 and only the new or different structures will be explained to most succinctly

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explain the additional advantages which come with the embodiments of the disclosure illustrated in FIG. 5.

The alternative embodiment system 10b of the disclosure shown in FIG. 5 may include a barrier 70 in the stack 28, and/or a taper 72 in the interior of the wall 18. It will be understood that the stack 28 may be positioned a distance from the orifice 34b such that as a vortex of fluid 74 is drawn into the chamber 20, the vortex will circulate within the chamber 20, as indicated by the path 76, to transfer heat out of the chamber 20. For example, one embodiment of the present disclosure includes a stack 28 positioned approximately one eighth of a wavelength from the first end 22 of the resonator 16. If the stack 28 is positioned too close to the orifice 34b, the vortex 74 may be drawn into the chamber 20, and expelled through the orifice 34b without circulating through the chamber 20. This may reduce the exchange of heat accomplished in the chamber 20. Also, if the vortex 74 impacts the stack 28, the vortex 74 may pass through the stack 28, thereby transferring heat from the cold end 46 of the stack 28 to the hot end 45 of the stack 28. This may create problems with the operation of the engine 14b. The barrier 70 may be formed as a solid member characterized by an absence of through passages. Also, the barrier 70 may be aligned with

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the orifice 34b and the barrier 70 may be sized and shaped so as to receive the impact of the vortex 74 to prevent the vortex 74 from flowing through the stack 28. The barrier 70 may direct the flow of the vortex 74 along the circulation path 76.

It will be understood that the taper 72 may provide the ability to independently vary the volume of the chamber 20 without varying other parameters of the thermoacoustic engine 14b, such as the wavelength. Also, the taper 72 may provide the ability to vary the position of a component with respect to a wavelength. The taper 72 may also serve to facilitate circulation of the vortex 74 through the chamber 20. The angle of the taper 72 may be configured to prevent the vortex 74 from sticking within the chamber 20 and to direct the vortex 74 to the orifice 34b. It will also be understood that the taper 72 may be formed in various different configurations, including linear surfaces formed at various different angles, or curved surfaces or concavities having various different radii of curvatures, or combinations of linear and curved surfaces. Moreover, it will be understood that the taper 72 may be formed beneath the stack 28 or on both ends of the resonator 16.

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It will be appreciated that the structure and apparatus disclosed herein are merely examples of a means for forming a synthetic jet, and it should be appreciated that any structure, apparatus or system for forming a synthetic jet which performs functions the same as, or equivalent to, those disclosed herein are intended to fall within the scope of a means for forming a synthetic jet, including those structures, apparatus or systems for forming a synthetic jet which are presently known, or which may become available in the future. Anything which functions the same as, or equivalently to, a means for forming a synthetic jet, whether by converting heat to acoustic power or otherwise, falls within the scope of this element.

In accordance with the features and combinations described above, a useful method for cooling an object includes the steps of:

(a) joining a thermoacoustic engine with the object;

(b) using heat in the object to power the thermoacoustic engine; and

(c) using the thermoacoustic engine to form a synthetic jet to move energy in the form of the heat away from the object.

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Those having ordinary skill in the relevant art will appreciate the advantages provide by the features of the present disclosure. For example, it is a feature of the present disclosure to provide a cooling device which is simple in design and manufacture, which may have no moving parts. Another feature of the present disclosure is to provide such a cooling device that utilizes the heat that is to be removed to power the cooling device such that no additional energy is required to power the device. It is a further feature of the present disclosure, in accordance with one aspect thereof, to provide a cooling device that is reliable. It is an additional feature of the present disclosure to provide a cooling device that can be used without generating a sound that is perceptible to humans, or to provide a cooling device that generates a sound that can be used as an indicator.

In the foregoing Detailed Description, various features of the present disclosure are grouped together in a single embodiment for the purpose of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the claimed disclosure requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed

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embodiment. Thus, the following claims are hereby incorporated into this Detailed Description of the Disclosure by this reference, with each claim standing on its own as a separate embodiment of the present disclosure.

It is to be understood that the above-described arrangements are only illustrative of the application of the principles of the present disclosure. Numerous modifications and alternative arrangements may be devised by those skilled in the art without departing from the spirit and scope of the present disclosure and the appended claims are intended to cover such modifications and arrangements. Thus, while the present disclosure has been shown in the drawings and described above with particularity and detail, it will be apparent to those of ordinary skill in the art that numerous modifications, including, but not limited to, variations in size, materials, shape, form, function and manner of operation, assembly and use may be made without departing from the principles and concepts set forth herein.

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